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Scaling of lifting forces in relation to object size in whole body lifting

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Subjects prepare for a whole body lifting movement by adjusting their posture and scaling their lifting forces to the expected object weight. The expectancy is based on visual and haptic size cues. This study aimed to find out whether lifting force overshoots related to object size cues disappear or persist over a number of repeated lifts. In addition, the influence of the degree of alternation between load sizes, and the influence of knowledge of actual object weights prior to the lifts, were investigated with regard to their effect on force overshoots. Four experiments were performed using a large and a small box, each of 8.4 kg weight, and varying degrees of alternation between boxes. In two of the experiments, subjects were informed about the weight of the objects, while in the other two experiments they were not informed about the weight of the objects.

When boxes were lifted 15 times before switching to the other box, rapid diminishing of force scaling errors was observed. However, when boxes were alternated each lift or after three lifts, persisting force scaling overshoots were found in lifting the large box compared to the small one. When participants were given information regarding the actual object weight, force overshoots in the first pair of large and small box lifts were not different from overshoots in experiments where subjects were not informed about the weight of the objects. This shows that, for occupational lifting, risks related to force overshoots in lifting large objects can persist despite experience in lifting the objects and despite the use of labels indicating the weight of the objects.

Keywords: Lifting forces; Size cues; Low back load

1. Introduction

When subjects grasp and lift an object, they anticipate for the expected object weight. Consequently, a mismatch between expected and actual object weight could affect the

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kinematics and kinetics of a lifting movement. In pinch-grip lifting, large objects are lifted with higher lifting forces (Gordon *et al*. 1991a) and accelerations (Davis and Roberts 1976, Gordon *et al*. 1991a) than small objects of equal weight.

In whole-body lifting, subjects not only anticipate for the expected object weight by scaling their lifting forces, but also by adjusting their posture (Toussaint *et al*. 1998). Apart from slowing down a lifting movement, underestimation of object weight in whole-body lifting has been found to have only small effects on kinematics, low back loading and whole body balance (van der Burg *et al*. 2000, van der Burg and van Dieen 2001a). In contrast, overestimation of object weight was reported to result in an increase in low back loading and, in some cases, in a loss of whole body balance (Commissaris and Toussaint 1997). This is of practical importance in occupational ergonomics because many workers lift loads without knowing the weight of the objects. Even when they know the weight, it is not evident that they are able to scale their lifting forces without being affected by the size-cues of the object (Kingma *et al*. 1999).

After a large and a small object of equal weight have been lifted, the large object is usually perceived as being lighter than the small object. This so-called size–weight illusion (Charpentier 1891) appears to be robust in the sense that it holds for a large range of weights (Stevens and Rubin 1970), it persists after repeatedly lifting the same objects (Flanagan and Beltzner 2000) and it is manifest even when participants are told that the weights of the objects are equal (Flournoy 1894).

The robustness of the size–weight illusion suggests that even after repeatedly lifting the same object, subjects could fail to adequately anticipate for the object weight. In pinch-grip lifting of small and large objects in an alternating order, the size–weight illusion was found to persist over a large number of trials (Flanagan and Beltzner 2000). However, the force overshoot in lifting the larger object was found to decline rapidly (Flanagan and Beltzner 2000). In pinch-grip lifting, haptic size cues are generally not available because participants lift the objects with one hand by grasping a pinch-grip handle that does not co-vary in size with the object. In two-handed whole-body lifting, visual and haptic size cues will usually both be available. Haptic size cues are known to result in stronger illusions than visual size cues (Ellis and Lederman 1993). The question therefore arises how persistent force overshoots in lifting larger objects are in whole-body lifting. The current study was performed to find out whether, in whole-body lifting movements, with haptic and visual size cues being available, lifting force overshoots related to object size would either disappear or persist over a number of trials. Furthermore, it seems likely that the degree of alternation between small and large objects might influence the persistence of force overshoots. Therefore, the second aim was to establish the influence of the degree of alternation between boxes (i.e. switching between boxes after each lift, after a few (three) lifts or after a larger number (15) of lifts) on the persistence of force scaling errors in whole-body lifting. Finally, load knowledge was varied in order to find out whether force overshoots are found in whole-body lifting with and without prior knowledge of the object's weight.

2. Methods

2.1. *Participants*

Four groups of 20 healthy participants took part in four experiments after signing an informed consent form. For each experiment a different group of participants participated. Table 1 gives the participant characteristics. In Experiments 2 and 3, data from one participant were lost due to technical problems.

2.2. *Procedure*

All participants made whole-body lifting movements, lifting a large box (width x depth x height = 530 x 350 x 250 mm) and a small box (400 x 265 x 200 mm) with a volume ratio of 2.19. Both boxes weighed 8.4 kg and had handles on the sides. The handles were separated from the boxes by 45 mm and their tops were 8 mm below the top of the boxes. The handles (width x depth x height = 20 x 190 x 56 mm) were custom-made and contained force-transducers to register lifting forces. Participants started each lifting movement in an upright standing posture. After a starting signal, they bent forward in a sagittally symmetrical way, grasped the handles of the box and returned to upright standing, lifting the box to hip height. Participants were free to bend their legs as much as they wanted during lifting, but they were asked to maintain a constant lifting speed and a constant lifting technique over the series of lifting movements. In Experiments 1 – 3, the large box was placed on the floor and the small box was placed on a 50 mm platform so that the initial height of the handles was the same (with the top of the boxes 250 mm above floor level) for both boxes. The initial position of the centre of mass of both boxes was 260 mm in front of the toes in all experiments.

In all four experiments, half of the participants started lifting the small box and the other half of the participants started lifting the large box. In Experiment 1, participants lifted one box 15 times and then the other box 15 times. In Experiment 2, participants lifted one box three times and then lifted the other box three times. This series was repeated four times. In Experiment 3, a total of 20 lifting movements was performed, alternating between boxes after each lift. In Experiments 1 and 3, participants were told that both boxes weighed about 8.5 kg. In Experiment 2, participants were told only that the boxes weighed less than 15 kg, and not that their weight was equal. After analysing the data, it was decided to perform a fourth experiment, repeating Experiment 3 with more repetitions (now boxes were lifted 20 times each) and with the modification that participants were not informed about the weight of the box (except that it was less than 15 kg). To prevent fatigue due to the large number of repetitions in Experiment 4, the initial height of both boxes was increased by 466 mm so that the height of the tops of both boxes became 716 mm.

To check whether the size – weight illusion occurred, participants were asked to estimate the weight of the boxes in both experiments where they had not been informed about the exact object weight. Participants were asked to estimate the weight of the box after each lift in Experiment 2 and only after they had finished all lifting movements in Experiment 4.

Table 1. Details of the participants in each of the four experiments

	Males/ Females	Age (years)		Stature (m)		Body weight (kg)	
		mean	SD	m	SD	mean	SD
Experiment 1	12/8	24	2	1.79	0.09	73	6
Experiment 2	14/6	22	2	1.78	0.09	70	7
Experiment 3	13/7	27	4	1.74	0.07	71	8
Experiment 4	12/8	23	2	1.76	0.08	69	6

For all experiments, boxes were not hidden between lifting movements, so that participants were aware that the weight of the boxes remained equal over the course of the experiment. Prior to each experiment, the participant was asked to simulate the lifting movement a few times by performing the movement without touching the box. The participant was asked to increase the pace of these practice movements until the experimenter considered the movement fast enough to prevent a 'probing strategy' (i.e. sliding or tilting the load before actually lifting it in order to evaluate the object's weight). Subsequently, the participant was instructed to lift at this pace.

2.3. *Data collection and processing*

Vertical lifting forces were measured in both handles of the boxes using custom-made strain gauge force transducers. After analogue filtering with a fourth order low-pass Butterworth filter at a cut-off frequency of 10 Hz, forces were sampled at a frequency of 200 Hz. A digital fourth order filter, again with a cut-off frequency of 10 Hz, was applied to the digitized signals in reverse direction, to correct the phase shift caused by the analogue filter. Subsequently, forces of the left and right handle were summed. Box vertical accelerations were calculated by subtracting the box weight (mass x gravity) from this summed force signal, and dividing the result by box mass. A five-point Lanczos differentiator was used to calculate, from the summed force signal, the rate of change of the vertical force (which is denoted by 'force rate').

LED markers were attached to three corners of the boxes. The positions of the three markers were measured at a frequency of 200 Hz with a highly accurate (SD < 0.1 mm) automated 3D movement registration system (Optotrak). After (bi-directional) digital filtering of marker coordinates with a fourth order Butterworth filter at a cut-off frequency of 10 Hz, the data were used to reconstruct the centre of the box at each instant of time. The box centre position was differentiated digitally with a five-point Lanczos differentiator to obtain its linear velocity. A synchronization pulse, indicating the start of the sampling of the Optotrak system, was recorded with the force signals. The instant of lift-off of the box was defined as the first sample at which the upward force applied to the handles exceeded box mass times gravity.

2.4. *Statistical analysis*

For each lifting movement, the peak lifting force was calculated from the forces at the handles. Statistical analyses were applied for the four experiments separately. After pooling all trials within an experiment, a repeated measures ANOVA was applied with box size and repetition as within-subject factors and starting box (starting with either the small or the large box) as a between-subject factor. Dependent variables were peak force, peak force rate, peak velocity and a derived measure of peak acceleration to peak velocity ratio (avratio; as explained below). Post-hoc repeated measures ANOVA's were applied to each pair of large and small box lifts (comparing the nth large box lift with the nth small box lift), with box size as a within-subject factor and starting box as a between-subject factor. Finally, to test whether the effect of box size differed between experiments, data of the first small box lift and the first large box lift in all experiments were pooled and a repeated measures ANOVA was applied to all dependent variables described above, with 'experiment' as a between-subject factor and box size as a within-subject factor. Wilcoxon signed rank tests were used to compare large and small box weight estimates in Experiments 2 and 4.

2.5. *Additional analysis*

Consistently over experiments, peak forces (and therefore also acceleration peaks) averaged over subjects suggested an overshoot in the first lift of the large box. However, this overshoot did not reach significance in any experiment. Velocity peaks however, tended to be lower in lifting the large box than the small box, again without reaching statistical significance. A combination of large peak accelerations with lower peak velocities would suggest that participants corrected their force overshoot before the peak velocity was reached.

Closer inspection of individual velocity and force profiles revealed that some participants showed a substantially larger force peak in lifting the large box without an overshoot of the peak velocity. Other participants did not show an increased force peak but showed a reduced velocity peak (see figure 1 for two examples). The latter suggests that those participants had intended to lift the large box slower than the small box. It can be assumed that force overshoots cannot be corrected before the peak acceleration occurs (generally occurring within 100 ms) but can be corrected before the peak velocity occurs (after roughly 500 ms). Consequently, division of peak forces or peak accelerations by peak velocities would correct for any downscaling of the intended lifting speed in the large box. Therefore, an additional parameter, the peak acceleration to peak velocity ratio (which will be further denoted as avratio), was calculated and included in the statistical tests.

3. Results

The ANOVA results for the four experiments are given in table 2. Effects of starting box and interactions with starting box were not significant for almost all variables and are not shown.

In Experiments 2 and 3, data from one participant were lost due to technical problems, so that the results were analysed for 19 subjects, while the results for Experiments 1 and 4 were analysed for 20 subjects. In Experiments 2–4, a main effect of box size on the peak force and on the avratio was found, and in Experiments 3 and 4 a main effect of box size on the peak force rate was found. The interaction between box size and repetition was not significant for peak force, peak force rate or avratio in any of the Experiments 2–4 (see figure 2 and table 2). Together, these effects suggest a persistent lifting force overshoot in lifting the large box compared to the small one, when participants switch between boxes after each lift (Experiments 3 and 4) or after three lifts (Experiment 2). In Experiment 4, ANOVAs on the peak force and avratio in individual pairs of large and small box lifts showed that even after 20 pairs of lifts, force overshoots in lifting the large box did not diminish (figure 2). In experiments 2 and 3, a comparable pattern was seen, although the effect of box size did not reach significance in most ANOVAs on individual pairs of large and small box lifts.

The results of Experiment 1, where participants switched only once between boxes, contrast with those of Experiments 2–4. In Experiment 1, a significant interaction between box size and repetition but no main effect of box size was found on the peak force and on the avratio. In addition, a main effect of box size on peak force rate was found in this experiment, but this effect was a lower rather than a higher peak force rate in lifting the large box compared to the small box (table 2 and figure 2). In the last few lifts also peak forces and the avratio tended to be lower in lifting the large box than in lifting the small box, although significance was only reached for the avratio in the final

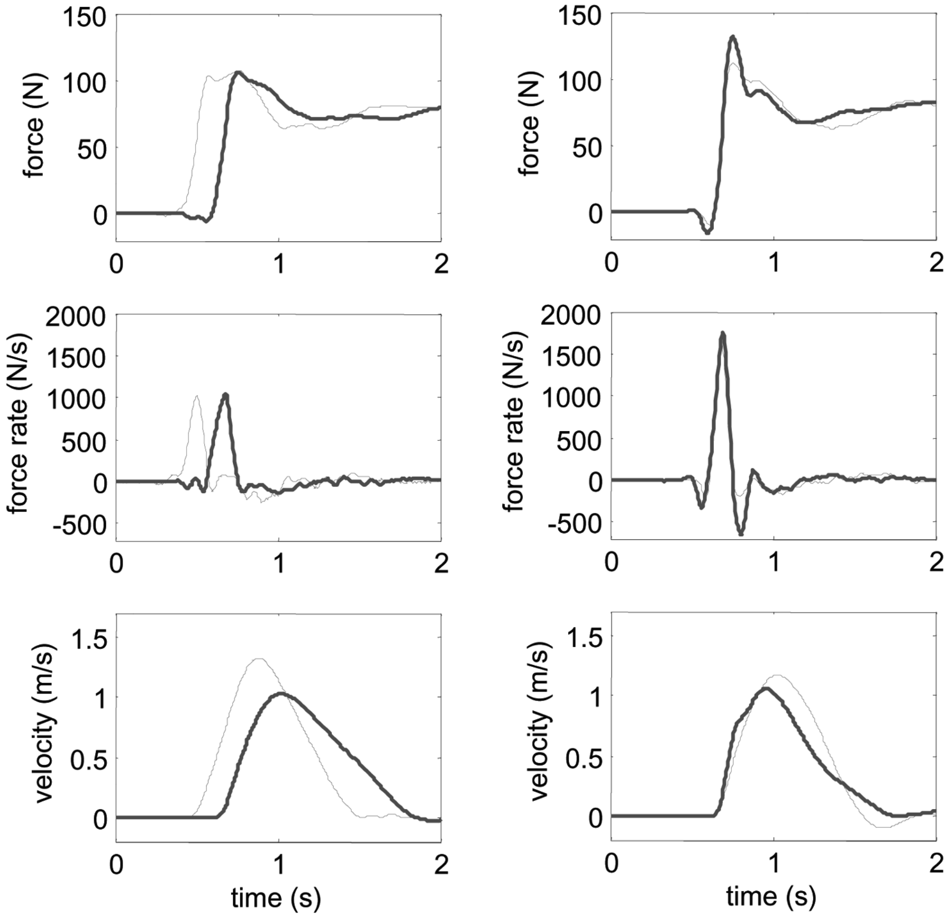

Figure 1. Force profiles (top row), force rate profiles (middle row) and velocity profiles (bottom row) of two typical first pairs of large (thick line) and small box (thin line) lifts in Experiment 4. The graphs on the left show a pair of trials from a subject tending to have an equal peak force but a lower peak velocity when lifting a large box compared to a small box. The graphs on the right show a subject tending to have a higher peak force and an almost equal peak velocity when lifting a large box compared to a small box.

trial. Thus, when switching only once between boxes, the force overshoots in lifting the large box quickly diminished, and even tended to reverse.

For all experiments, the pattern of avratio had an appearance that was very similar to the peak force (see figure 2). However, when testing differences between the large and small box in individual trials, it became apparent that, in whole-body lifting, the avratio is a more reliable indicator of force scaling overshoots than the peak force or the peak force rate. Over all experiments, the avratio reached significance in 27 pairs of lifting movements whereas significance was reached in 16 and 12 pairs for the peak force and peak force rate, respectively (figure 2). Surprisingly, the apparently large average difference between the large and small box peak force in the first pair of lifting movements (as shown in figure 2) was not significant in any of the experiments (p-values

Table 2. ANOVA results for the four experiments in which two boxes of equal weight (8.4 kg) but different volumes were lifted. The number of lifts performed is indicated, with the number of repeated lifts before switching to the second box shown in brackets

	Experiment 1		Experiment 2		Experiment 3		Experiment 4	
	(n = 20) lifts = 30 (15)		(n = 19) lifts = 24 (3)		(n = 19) lifts = 20 (1)		(n = 20) lifts = 40 (1)	
Effect of box size	F(1,18)	*p*-value	F(1,17)	*p*-value	F(1,17)	*p*-value	F(1,18)	*p*-value
peak force	0.269	0.611	8.153	**0.011**	5.085	**0.038**	28.594	< **0.001**
peak force rate	10.616	**0.004**	0.180	0.676	7.180	**0.016**	11.608	**0.003**
peak velocity	0.910	0.353	2.567	0.128	1.655	0.216	12.027	**0.003**
peak acceleration / peak velocity ratio	< 0.001	0.986	22.081	< **0.001**	11.074	**0.004**	49.832	< **0.001**
Effect of repetition	F(14,252)	*p*-value	F(9,153)	*p*-value	F(11,187)	*p*-value	F(19,342)	*p*-value
peak force	1.252	0.238	1.228	0.282	1.300	0.227	0.879	0.609
peak force rate	0.898	0.546	0.509	0.748	0.034	0.857	0.662	0.599
peak velocity	0.812	0.655	1.435	0.178	0.616	0.814	2.211	**0.003**
peak acceleration / peak velocity ratio	2.292	**0.006**	2.839	**0.004**	1.332	0.209	1.724	**0.031**
Effect of box size x repetition	F(14,252)	*p*-value	F(9,153)	*p*-value	F(11,187)	*p*-value	F(19,342)	*p*-value
peak force	2.160	**0.010**	1.197	0.301	1.051	0.404	0.528	0.950
peak force rate	0.644	0.812	0.977	0.464	2.000	**0.048**	0.861	0.547
peak velocity	1.299	0.208	0.342	0.960	1.230	0.269	2.232	**0.002**
peak acceleration / peak velocity ratio	3.427	< **0.001**	0.749	0.663	1.528	0.124	0.666	0.852

Bold numbers indicate significant *p*-values ($p < 0.05$).

ranged from 0.065 to 0.172). This may reflect a more cautious approach in lifting the large box by some subjects (see figure 1), since the avratio differed significantly between the large and small box in the first trial in all experiments.

Since half of the participants started lifting the small box, whereas the other half started lifting the large box, starting box was included as a between-subject factor in all ANOVAs. However, no effect of starting box was found in any of the four experiments and the interaction between starting box and box size was only significant for the avratio in Experiment 2.

An ANOVA performed over the results for the first small box lift and the first large box lift of the pooled experiments revealed no significant interaction effect of experiment and box size on peak force, peak force rate, peak velocity or avratio (for all variables, $F[3, 74] < 0.43$, $p > 0.637$). Since participants were informed about the actual weight of the boxes in Experiments 1 and 3, but not in Experiments 2 and 4, this suggests that the strength of the overshoot in force scaling was not affected by telling the participants the weight of the boxes. However, there was a main effect of experiment on peak force, peak force rate, peak velocity and avratio (for all variables, $F[3, 74] > 3.3$, $p < 0.025$), which may have been due to (unintended) variations in lifting instructions between experiments and due to the change in lifting height in Experiment 4.

In Experiment 2, weight estimation by the participants (see table 3) revealed a size–weight illusion in 12 out of 19 participants comparing the first lifts of both boxes and in

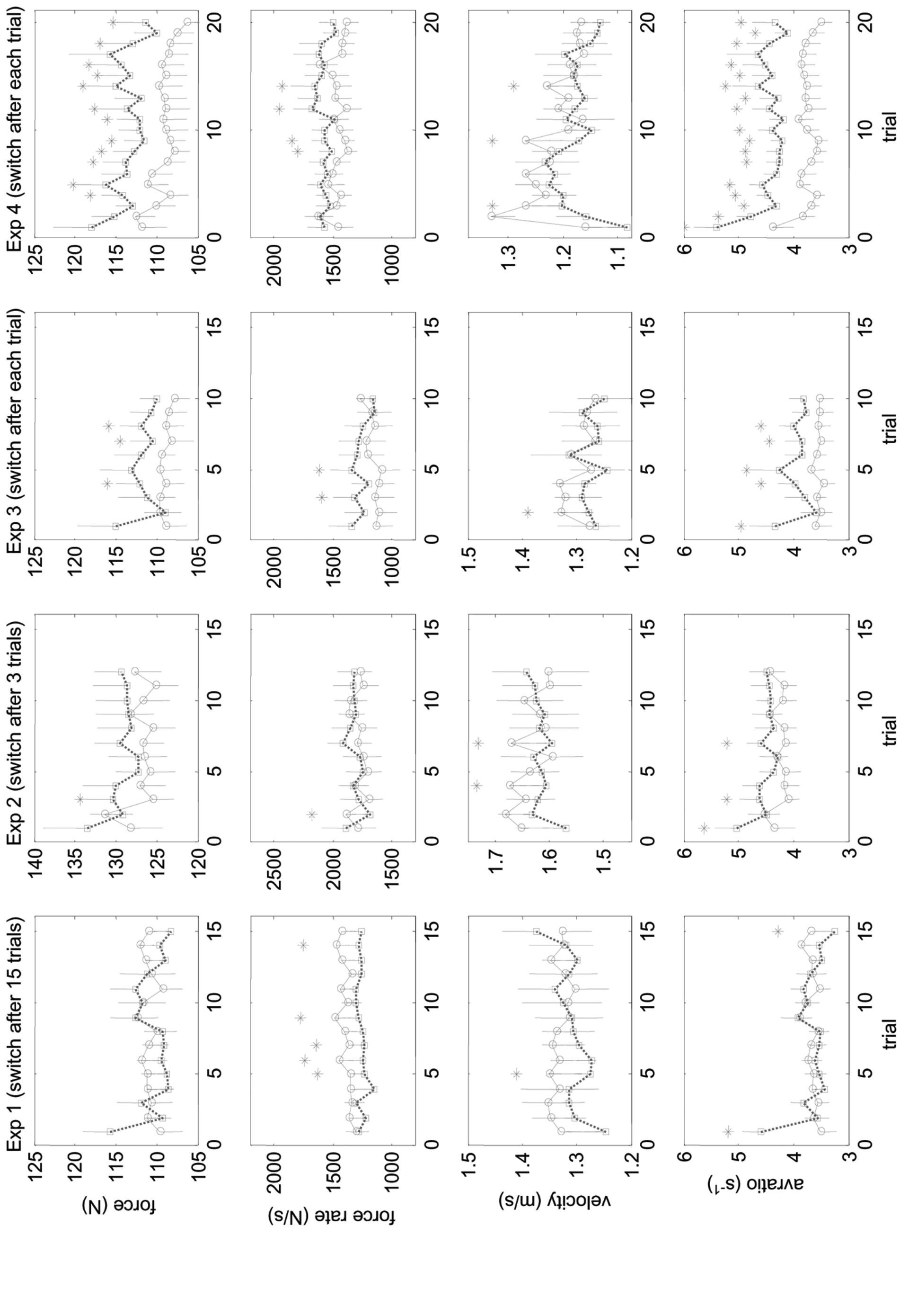
Exp 1 (switch after 15 trials)
Exp 2 (switch after 3 trials)
Exp 3 (switch after each trial)
Exp 4 (switch after each trial)
force (N)
force rate (N/s)
velocity (m/s)
avratio (s-1)
trial

Table 3. Weight estimate differences between the small and the large box, after the first large and small box lifts of Experiment 2, after the last large and small box lifts of Experiment 2 and after the last large and small box lifts of Experiment 4. p-Values indicate results from a Wilcoxon signed rank test on weight estimates

	Experiment 2 first trial	Experiment 2 last trial	Experiment 4 last trial
Participants estimating small box heavier (n)	12	14	15
Participants estimating boxes equal (n)	5	5	5
Participants estimating large box heavier (n)	2	0	0
Maximum small – large box weight estimate (kg)	9.00	5.00	7.00
Minimum small – large box weight estimate (kg)	–2.00	0.00	0.00
Median small – large box weight estimate (kg)	1.00	1.00	1.75
Size – weight illusion test (p-value)	0.012	0.001	0.001

14 out of 19 participants comparing the last lifts of both boxes. This was quite comparable to Experiment 4 (15 out of 20 participants), where participants were asked only to estimate box weights after the last pair of lifting movements.

4. Discussion

The main finding in this study was a persistent overshoot in lifting force for lifting a large box compared to a small box of equal weight, when these boxes were lifted in an alternating way while using a two-handed whole-body lifting style. The overshoot in the first pair of lifts was not influenced by knowledge of the actual box weights. This overshoot might induce an increased low back loading and might also be a potential threat to whole body balance.

The avratio was introduced in this study to correct for any downscaling of the intended lifting speed in the large box. Although tendencies of the peak forces were very similar (figure 2), the avratio appeared to be more sensitive to box size effects. It might well be the case that the more cautious approach in lifting the large box by some participants, which probably underlies this difference in sensitivity, is specific to whole-body lifting, due to potential threats to low back loading and whole body balance. It should be realized, however, that the actual lifting force rather than the avratio is related to low back loading.

In contrast to the current results when alternating lifts between large and small boxes (Experiments 3 and 4), Flanagan and Beltzner (2000) found that force overshoots in lifting a large object, compared to a small object, do diminish after a few trials. Most likely this difference in findings is related to the type of size cues available to the

Figure 2. Peak lifting force (top row), peak force rate, (second row), peak velocity (third row) and peak acceleration to peak velocity ratio (avratio, bottom row) in Experiments 1 – 4. In Experiment 1 participants did not alternate between boxes, in Experiment 2 they alternated after three lifts and in Experiments 3 and 4 they alternated after each lift. Average values of 19 (Experiments 2 and 3) or 20 (Experiments 1 and 4) participants are given. Trials for the large box are shown by squares, connected with a dotted line and upward error bars (indicating one SEM). Trials for the small box are shown by circles, connected with a solid line and downward error bars. Asterisks indicate a significant effect of box size for the nth large box lift vs. the nth small box lift.

participants in the two studies. Flanagan and Beltzner (2000) used a set-up that provided only visual size cues, whereas the current study used one that combined visual and haptic size cues. Haptic size cues are known to result in stronger illusions as compared to visual size cues (Ellis and Lederman 1993). In precision grip lifting, where participants were allowed to haptically explore the size of an object prior to lifting, Gordon *et al*. (1991b) also reported persistent size effects on force scaling when objects were lifted in an alternating way.

A comparison between the experiments in the current study showed that the degree of alternation between boxes influenced the persistence of size effects on force scaling. In Experiment 4, where boxes were alternated after each lift, force-scaling differences did not diminish, even after 20 pairs of lifts. In contrast, in Experiment 1 where 15 lifts of each box were performed consecutively, the effect of box size on the scaling of peak forces disappeared. This is in agreement with Gordon *et al*. (1991b), who reported that haptic size effects disappeared when objects were lifted consecutively with pinch-grip lifting.

Lifting technique cannot be excluded as a factor affecting the scaling of initial lifting forces in whole-body lifts. The wider arm spread that is needed to lift the large box could have affected the lifting forces. However, such an effect would, in contrast to the current results, be expected to be constant within and between experiments. Moreover, a reduction in lifting force would be expected given that shoulder moments at constant lift force increase with increasing abduction of the arms.

In Experiment 4, where the initial position of the boxes was higher than in Experiments 1–3, the difference in force scaling between the small and the large box was larger and more frequently statistically significant. It has been shown that, when lifting objects from the ground, lifting movements are very robust in the sense that they are hardly influenced by an unexpected weight increase up to 10 kg (van der Burg *et al*. 2000, van der Burg and van Dieen 2001b). Possibly, participants rely in part on this robustness when lifting from the ground, whereas lifting from a higher position evokes more explicit anticipation in terms of force scaling because the trunk inertia and pre-existing trunk muscle activity (which increases trunk stiffness) are of less help. This would suggest that the risks that might be associated with force overshoots when lifting large objects (i.e. increased low back loading or loss of whole body balance) are more pronounced when objects are lifted from a location higher than the floor.

The present experiments have shown that overshoots in force scaling can persist when size cues are strong enough (i.e. when they are both haptic and visual) and when those cues are reinforced by alternating between boxes. In addition, weight estimates by the participants in Experiments 2 and 4 showed that, in whole-body lifting, the size–weight illusion occurs and persists after many lifts in the majority of subjects. This does not mean that there is a direct link between force overshoots and the size–weight illusion. Pinch-grip lifting experiments (with only visual size cues) have shown that the illusion can occur in the absence of force overshoots (Mon-Williams and Murray 2000) and can persist after force overshoots have vanished (Flanagan and Beltzner 2000).

In terms of the consequences for occupational practice, the results of the current study should be interpreted with care. It should be kept in mind that occupational lifting often involves asymmetric lifts with objects that may not have handles. It is unknown whether the current results would hold for asymmetric lifting or for lifting without handles. In addition, experienced lifters often use a strategy of tilting an object prior to lifting it (Gagnon 2003), which may help to evaluate the weight. Therefore, the large force overshoot that was found in the first set of lifts may be of limited practical relevance. However, the persisting somewhat smaller force overshoot in subsequent lifts of larger objects, as observed in the current study, may be more important. Focusing on this persisting overshoot, the current results imply that workers are more at risk when lifting boxes that are large for their weight than when lifting boxes with a more usual ratio between weight and size, especially when box sizes are frequently alternated. The main reason is that large boxes are persistently lifted with larger peak forces, which are likely to cause higher compression forces in the lumbar spine. This adds to the effect of moment arm. Moment arms were kept the same for large and small boxes in the current study, but are likely to cause an additional increase low back loading when lifting large boxes in an occupational environment. When the discrepancy between actual and expected box weight is larger than in the current study, such as when lifting a large box that is unexpectedly empty, force overshoots could induce balance problems, because postural adjustments are likely to be scaled to a larger object weight. Finally, the current results show that (cognitive) knowledge of the actual object weight, which is often provided by attaching labels to boxes, does not prevent force overshoots in lifting larger objects. It remains to be investigated whether evaluation of a load, through tilting or shifting it prior to lifting it, would prevent this overshoot.

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